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Assessment of satellite rainfall products over the Andean plateau

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ABSTRACT

Nine satellite rainfall estimations (SREs) were evaluated for the first time over the South American Andean plateau watershed by comparison with rain gauge data acquired between 2005 and 2007. The comparisons were carried out at the annual, monthly and daily time steps. All SREs reproduce the salient pattern of the annual rain field, with a marked north–south gradient and a lighter east–west gradient. However, the intensity of the gradient differs among SREs: it is well marked in the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis 3B42 (TMPA-3B42), Precipitation Estimation from remotely Sensed Information using Artificial Neural Networks (PERSIANN) and Global Satellite Mapping of Precipitation (GSMaP) products, and it is smoothed out in the Climate prediction center MORPHing (CMORPH) products. Another interesting difference among products is the contrast in rainfall amounts between the water surfaces (Lake Titicaca) and the surrounding land. Some products (TMPA-3B42, PERSIANN and GSMaP) show a contradictory rainfall deficit over Lake Titicaca, which may be due to the emissivity contrast between the lake and the surrounding lands and warm rain cloud processes. An analysis differentiating coastal Lake Titicaca from inland pixels confirmed this trend. The raw or Real Time (RT) products have strong biases over the study region. These biases are strongly positive for PERSIANN (above 90%), moderately positive for TMPA-3B42 (28%), strongly negative for CMORPH (−42%) and moderately negative for GSMaP (−18%). The biases are associated with a deformation of the rain rate frequency distribution: GSMaP underestimates the proportion of rainfall events for all rain rates; CMORPH overestimates the proportion of rain rates below 2 mm day^{-1}; and the other products tend to overestimate the proportion of moderate to high rain rates. These biases are greatly reduced by the gauge adjustment in the TMPA-3B42, PERSIANN and CMORPH products, whereas a negative bias becomes positive for GSMaP. TMPA-3B42 Adjusted (Adj) version 7 demonstrates the best overall agreement with gauges in terms of correlation, rain rate distribution and bias. However, PERSIANN-Adj's bias in the southern part of the domain is very low.

1. Introduction

Precipitation affects many economic activities, such as agriculture, industry, transport and tourism. It is also a key variable for improving water resource management and flood or drought forecasting, as well as for hydrological research or climatology. For all these applications, accurate rainfall estimation is required worldwide, but in many regions, rain gauge coverage is sparse. This is particularly true in remote regions such as the Andean plateau in South America where ground gauges are unevenly distributed; they are mainly located close to cities or communities to facilitate maintenance operations. Consequently, some areas in the Andean plateau are relatively well monitored, but a large number of areas are not monitored at all. In a region where rainfall is highly variable, extrapolating from a sparse and unevenly distributed rain gauge network leads to inaccuracies (Li and Heap, 2008; Scheel et al., 2011). Moreover, in the Andean plateau, most of the rain gauge data are still collected manually. Collecting and digitizing the information introduces uncertainties in the time series and delays the availability of data. Rainfall data availability is even more complicated in trans-boundary watersheds like the Andean plateau, which is shared by three countries, because of potential water use conflicts. With global spatial coverage, good spatio-temporal resolution and online availability, satellite rainfall estimates (SREs) represent an attractive alternative solution.

SREs are based on a combination of data from different passive micro-wave (PMW) and infra-red (IR) radiometers on board low earth-orbiting (LEO) and geosynchronous (GEO) satellites, respectively. Depending on the region and rainfall regimes, the biases introduced by either type of sensor may impact the final combined product. Due to the irregular sampling of LEOs and the limited number of overpasses, short rainfall events are not well captured by PMWs (Tian et al., 2009; Gebregiorgis and Hossain, 2013). This can explain the reduced accuracy of some SREs (TMPA-3B42-RT and Adj v6, CMORPH) in arid regions or

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during the dry season when short rainfall events are predominant (Prakash et al., 2014; Shen et al., 2010; Yang and Luo, 2014; Gao and Liu, 2013). Researchers also agree that rain/no rain classification based on cloud top IR temperature may fail in mountainous regions (Dinku et al., 2007, 2010; Hirpa et al., 2010; Li et al., 2013; Gebregiorgis and Hossain, 2013). The threshold used might be too low to identify orographic warm clouds as rainy. PMWs may also introduce errors in mountainous regions because snow and ice surfaces may be interpreted as rainy clouds (Dinku et al., 2010). SREs tend to underestimate precipitation over large water bodies (Paiva et al., 2011; Tian et al., 2007; Katiraie-Boroujerdy et al., 2013). Tian et al. (2007) attribute this inconsistency to a misinterpretation of the PMWs' emissivity over water surfaces. Paiva et al. (2011), working in the Amazon basin, attributed the underestimation of rainfall over the river to the river breeze effect that locally reduced rainfall amounts. Products like Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis 3B42 (TMPA-3B42; hereafter called TMPA), Climate prediction center MORPHing (CMORPH) and Global Satellite Mapping of Precipitation (GSMaP) rely heavily on the instant rain retrieval data derived from the PMW information from LEOs. Due to the insufficient number of overpasses from LEOs, IR data are used to fill in the gaps between the PMW estimates. Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) uses a different approach. The rainfall amount is first estimated through IR data, and the PMW information is used to improve the accuracy of the estimate. These four combined products have versions based only on PMW and IR data available with a short delay (and referred to as RT for real time or RAW hereafter) and Adjusted versions that ingest rain gauge information to reduce the biases are available with longer delays (they are referred to as Adj hereafter).

To our knowledge, there are only two published works on the performance of SREs over the Andean plateau. The first (Heidinger et al., 2012) focused on a correction methodology for TMPA-Adj v6. Their method improves TMPA-Adj v6 agreement with rain gauge daily data but is strongly dependent on the availability of rain gauges. The second paper assessed TMPA-RT v7, Modern-Era Retrospective Analysis for Research and Applications (MERRA), Climate Forecast System Reanalysis and Reforecast (CFSR) and a combined scheme product (CoSch) using both rain gauges and TMPA-RT v7 rainfall estimation over the Bolivian Altiplano watershed part on a coarse scale (0.5°) and daily basis (Blacutt et al., 2015). Over the studied period (1999–2009), CoSch outperformed the other SREs in terms of categorical statistics, STD, RMSE, bias and correlation, followed by TMPA-RT v7, CFSR and MERRA. For the rainy season, TMPA-RT v7 outperformed the other SREs in terms of STD, RMSE and bias, and its categorical statistics are very close to CoSch's. As only three rain gauges were used, these results have to be considered as preliminary, and comparison with a denser rain gauge network is still needed to assess TMPA-RT v7 performance over the Andean plateau. Apart from Salio et al. (2014) over South America, Buarque et al. (2011) in the Amazon and Dinku et al. (2010) in the Colombian Andes, who included CMORPH in their study, only the TMPA products have been assessed over South America (Collischonn et al., 2008; Getirana et al., 2011; De Paiva et al., 2013; Su et al., 2008; Vila et al., 2009; Condom et al., 2010; Zulkafli et al., 2014; Ochoa et al., 2014; Scheel et al., 2011), and SRE intercomparison is not available for the Andean plateau. This is one reason for the present work. It should also be noted that no common conclusion could be drawn from the various SRE intercomparison studies that have been carried out around the world. Even if focusing only on the four PMW-IR combined products cited above (TMPA, CMORPH, PERSIANN and GSMaP), the conclusions of the intercomparison exercise vary among studies, and no product outperforms the others in all conditions. When considering CMORPH, PERSIANN-RT and TMPA-Adj v6, TMPA-Adj v6 was found more suitable to describe both daily and monthly precipitation over China with better categorical statistical results and both lower bias and higher correlation (Yang and Luo, 2014). Considering the same SREs, TMPA-Adj v6 was found to best reproduce some hydrological features (annual amounts over catchment, spatial distribution patterns, seasonality, number of rainy days per year, timing and volume of heavy rainfall events) in four African watersheds (Thiemig et al., 2012). CMORPH was found to perform better at a daily time step in terms of categorical statistics than TMPA-Adj and RT v5 in the mountainous areas of South America (Dinku et al., 2010) and to present lower bias for monthly and 10-day time steps in Africa (Dinku et al., 2007). Considering seasonal bias, PERSIANN-RT was more accurate than CMORPH and TMPA-RT in northwest Ethiopia (Romilly and Gebremichael, 2010). On the contrary, in West Africa, many authors (Gosset et al., 2013; Casse et al., 2015) found that PERSIANN-RT has by far the strongest bias compared to the two other RT products. The results for SRE quality can also vary in the same study area so that no particular SRE is found to be outperform the others in detecting daily rainfall (Gebregiorgis and Hossain, 2013) or determining seasonal and spatial monthly rainfall characteristics (Asadullah et al., 2008). The latter authors have suggested combining all SREs to optimize rainfall estimations. In comparison with other SREs, GSMaP is less documented. Over the continental United States, GSMaP-RAW v4 was found to successfully capture the seasonal spatial pattern of precipitation, and its global performance was similar to CMORPH, PERSIANN-RT and TMPA-Adj v5 (Tian et al., 2010). In China, TMPA-Adj v7 outperformed CMORPH and GSMaP-RAW v5 in terms of continuous and categorical statistics on a daily basis (Qin et al., 2014).

Our study compares nine of the most commonly used SREs with rain gauges over the Andean plateau. The objective is to determine which products have the best agreement with rain gauges, with foreseeable applications in the field of hydrology. Both real-time (or short release delay) and post-adjusted products are evaluated, as their scope of applications is complementary: RT or RAW products are necessary for some operational applications such as flood forecasting, while post-adjusted (i.e., supposedly unbiased) products are preferable for process studies or hydro-climatology purposes. Comparing both RT and adjusted versions against rain gauges is also necessary, as some studies have suggested that the adjustment may increase uncertainties in some areas (Bitew and Gebremichael, 2011); however, most studies have found that adjustment improves the products (Gourley et al., 2010; Shen et al., 2010; Dinku et al., 2010; Gosset et al., 2013; Gao and Liu, 2013; Chen et al., 2013). This is also an opportunity to verify how TMPA-Adj v7 and v6 compare over the Andean Plateau. This is the first comparison of the PERSIANN and GSMaP products against rain gauges in South America. In arid conditions similar to those of the Andean Plateau, Katiraie-Boroujerdy et al. (2013) found that TMPA-Adj v6 and PERSIANN-Adj behaved similarly in Iran. Because CMORPH has been found to perform well over mountainous areas (Dinku et al., 2007, 2010), the new CMORPH-RAW and its adjusted version, CMORPH-Adj, are tested in our study.

Trapped between high relief, with lake and salt areas accounting for close to 10% of the total area (Satgé et al., 2015), the arid region of the Altiplano presents all the typical features for which SREs suffer strong uncertainties. Assessing the behavior of nine commonly used SREs in this region is therefore instructive. This study is a step towards using SREs over the Andean plateau for hydrological applications. The evaluation is focused on rainfall characteristics that are important for assessing the water budget over the region and for understanding processes: rainfall spatial variability, seasonal variability, monthly correlations, biases and the detection and distribution of daily rainfall. Given the limited number of rain gauges in the study area, small spatial temporal features are not assessed.

2. Study area

The Altiplano watershed is an endoreic system located between latitude 22°S and 14°S and longitude 71°W and 66°W. Three countries contribute to this area: Bolivia (70%), Peru (26%) and Chile (4%). The total area is approximately 192,000 km^2. Elevations range between